



OBSTACLE DETECTORS FOR AUTOMATED TRANSIT VEHICLES: A TECHNOECONOMIC AND MARKET ANALYSIS

Conducted for the

TECHNOLOGY TRANSFER DIVISION
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

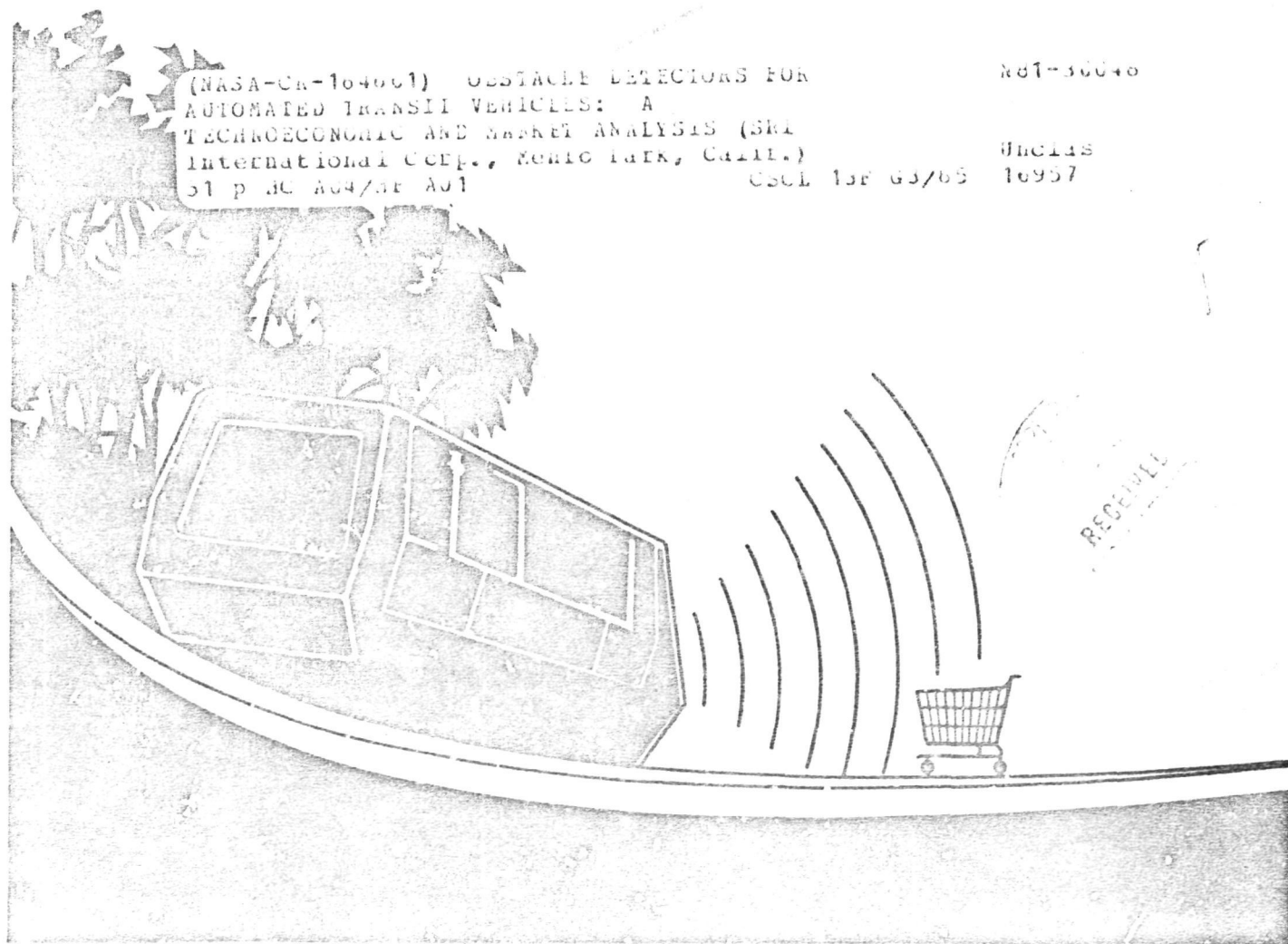
(NASA-CR-164661) OBSTACLE DETECTORS FOR
AUTOMATED TRANSIT VEHICLES: A
TECHNOECONOMIC AND MARKET ANALYSIS (SRI
International Corp., Menlo Park, Calif.)
51 p. HC A04/AF A01

N81-30048

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CSCL 15F G3/65 16957

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OBSTACLE DETECTORS FOR AUTOMATED TRANSIT VEHICLES: A TECHNOECONOMIC AND MARKET ANALYSIS

December 1979

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Prepared for:

National Aeronautics and Space Administration
Technology Transfer Division
Code ETT-6
Washington, D.C. 20546

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Contract NAS2-10143

SRI Project 8136

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PREFACE

Generating broad implementation of NASA technology and expertise increases the return on the nation's investment in aerospace research. Under contract to NASA's Terrestrial Applications Branch, the NASA Technology Applications Team at SRI International works toward this goal of extending technology use by transferring aerospace technology to solve key problems in the transportation and public safety fields.

Providing an important intermediary role between technology sources and technology users, the SRI Team assists in the movement of new technology across organizational and disciplinary boundaries, improves communications and shortens the time between technological development and broad and effective application.

This analysis of the market for collision avoidance systems for automated transit vehicles was conducted as part of the SRI Team's transportation effort.

GLOSSARY

AGT	-	Automated Guideway Transit
AMTV	-	Automated Mixed Traffic Vehicle
DOT	-	Department of Transportation
DPM	-	Downtown People Mover (project)
EPN	-	Electric Pedestrian Mover
GM	-	General Motors
GRT	-	Group Rapid Transit
GRIPS	-	Guided Radar Information Processing System
JPL	-	Jet Propulsion Laboratory
LTV	-	Light Transit Vehicle
PRT	-	Personal rapid transit
SLT	-	Shuttle-loop transit
UMTA	-	Urban Mass Transportation Administration

I INTRODUCTION

During the past few years, interest has been renewed in the use of fully automated transit systems as a solution to many current and anticipated transportation problems in the urban areas of the United States. However, an economical method has not yet been established for remotely detecting potential obstacles in the vehicle guideway within sufficient time to avoid collision.

Automated systems offer the promise of convenient, dependable service and could replace or complement present urban transportation systems. Various types of automated guideway transit (AGT) systems and an automated mixed traffic vehicle (AMTV) system have been proposed to supplement services provided by present systems. However, many technological problems such as network operation, vehicle control, safety (e.g., collision avoidance), reliability, and maintainability must be resolved before major operations can be started.

This technoeconomic and market analysis was prompted by requests for obstacle detector technology by the Urban Mass Transportation Administration (UMTA) and the Transportation Systems Center of the U.S. Department of Transportation (DOT). In response, SRI conducted a technology search to identify the technical and economic characteristics of both NASA and non-NASA obstacle detectors. The findings, along with market information, are compiled and analyzed in this report for consideration by DOT and NASA in decisions about any future automated transit vehicle obstacle detector research, development, or applications project.

Currently available obstacle detectors and systems under development are identified by type (sonic, capacitance, infrared/optical, guided radar, and probe contact) and compared with the three NASA devices selected as possible improvements or solutions to the problems in existing obstacle detection systems.

Sections V and VI present cost analyses and market forecasts individually for the AGT and AMTV markets.

II BACKGROUND AND DEFINITIONS

Automated Guideway Transit Systems

AGT systems are types of urban transportation systems and concepts in which automatically controlled, driverless vehicles on fixed, dedicated guideways are used. The capacity of a vehicle can be from 1 to 100 passengers, and the vehicles travel at speeds of up to 40 mph.

AGT systems have been classified in the following three categories:

- Shuttle-loop transit (SLT)
- Group rapid transit (GRT)
- Personal rapid transit (PRT).

These AGT classes are briefly described* as follows.

Shuttle-Loop Transit (SLT)--In an SLT system, large vehicles (carrying mostly standees) are used. The vehicles operate in scheduled service on relatively short lengths of dedicated guideway in activity centers, normally without switching. The shuttles accommodate a single vehicle within the dedicated lane. Headways are generally in excess of 1 minute in loops.

The Tampa International Airport has an example of SLT, shown in Figure 1. The central building of the terminal is connected to each of the four satellites by 305-meter-long elevated guideways, each containing two passenger vehicles on separate tracks and a walkway for emergency use. The average trip time, counting waiting time and riding, is 1½ minutes. The vehicles cover the 1,000 feet at a top speed of 28 mph.

* Excerpted from UMTA-VA-06-0041-78-1, dated February 1978.

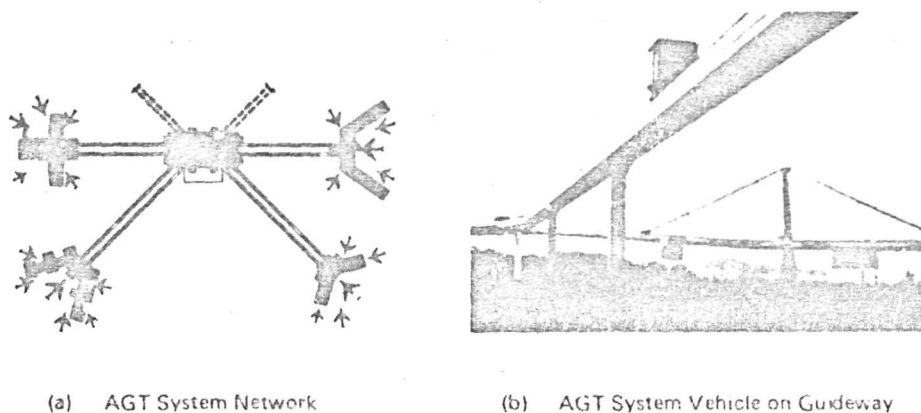
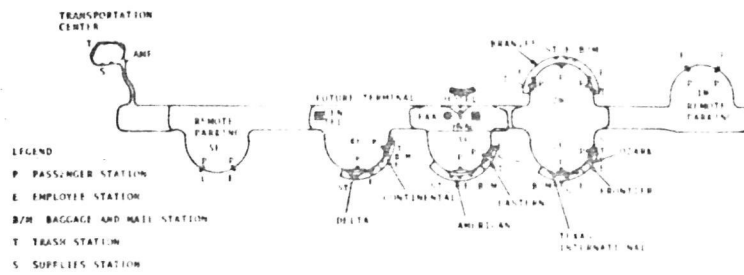


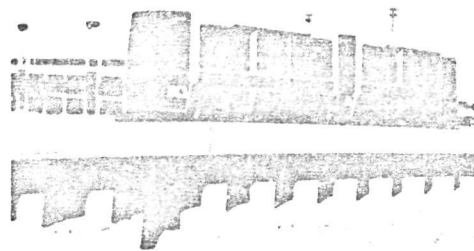
FIGURE 1. TAMPA AIRPORT SLT SYSTEM IN TAMPA, FLORIDA

Group Rapid Transit (GRT)--In GRT systems, fleets of medium-size vehicles usually 15 to 30 seated passengers per vehicle are used. These vehicles operate independently or are coupled into trains and travel automatically on dedicated guideways with on-line and/or off-line stations; they provide either scheduled or limited-stop, origin-to-destination, demand-responsive service. When operated on headways of 10 to 60 seconds, lane capacities ranging from 2,500 to 25,000 seats per lane per hour are obtained (up to 360 vehicles per lane per hour for 10-car trains).

Figure 2 shows the Dallas/Fort Worth Airport GRT, AIRTRANS. The AIRTRANS system links the numerous, widely separated elements of the airport. Approximately 13 miles of one-way guideway carry 68 vehicles between 55 station stops. Seventeen distinct service loops provide for passenger, airport employee, baggage, and mail transportation.



(a) Airtrans System Network

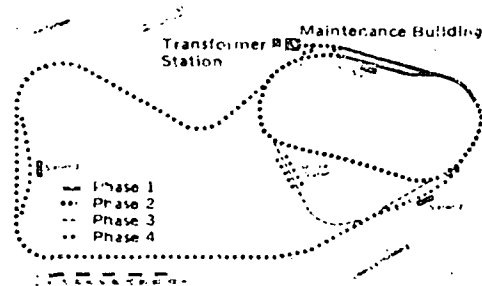


(b) Airtrans Vehicles on Guideway

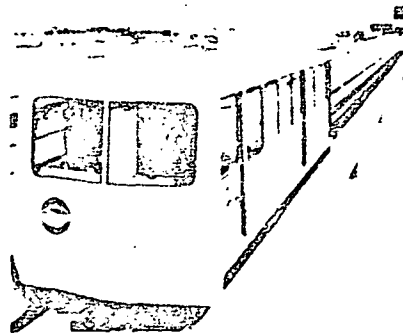
FIGURE 2. AIRTRANS GRT SYSTEM IN DALLAS, TEXAS

Personal Rapid Transit (PRT)--In PRT systems, fleets of small vehicles (usually of automobile size) are used that travel automatically on dedicated guideways with off-line stations to provide nonstop origin-to-destination, demand-responsive service. High capacities of 30,000 or more seats per lane per hour are achieved by operating the vehicles at short headways (2 to 3 seconds) that is, up to 18,000 vehicles per hour per lane.

The Cabintaxi test track at Hagen, West Germany, shown in Figure 3, is an example of PRT. These small, three-person vehicles (no standees) are designed to travel at speeds of up to 22 mph, at headways of 1 second and less, between off-line stations.



(a) Cabintaxi System Test Facility Network in Hagen



(b) Cabintaxi Vehicles on Test Track

FIGURE 3 CABINENTAXI PRT SYSTEM IN HAGEN, WEST GERMANY

At present approximately 20 AGT systems are in operation in the United States. Ten more AGT systems are being used for technology development and testing. Emphasis in the United States has been on the deployment of operating systems, whereas foreign programs have focused on prototype development and testing. Consequently, domestic programs have been characterized by the use of more conservative technological developments aimed at producing hardware for near-term applications (such as the Dallas/Fort Worth AIRTRANS, and Morgantown, West Virginia, systems).

Table 1 is an overview of the significant AGT developments in the United States. This table shows the dimensions, weights, and capacities of the vehicles, lists the major performance attributes (speed, headway, passenger carrying capacity), and indicates current development status.

In addition to the AGTs identified in Table 1, the Downtown People Mover (DPM) demonstration project has been funded by UMTA for \$220 million. Guidelines for these AGT demonstrations require that whenever possible, a different technology be used in each of the five cities chosen (Miami, Detroit, St. Paul, Houston, and Los Angeles) so that federal planners can evaluate which people mover systems work best. Actual routes, configurations, and equipment have not yet been chosen.

Because current AGT systems operate in relatively protected environments, the need for an obstacle detector has not been pressing. Sixteen of the 20 operating U.S. systems shown in Table 1 have had no recorded collisions. AIRTRANS had trouble with luggage falling from an overhead transport system onto the guideway; without an obstacle detector, the AIRTRANS vehicles would hit the luggage. This problem was solved with the addition of a probe that stopped the vehicle when contacted.

However, DPMs will not operate in secure environments. Thus, a cost-effective obstacle detector is expected to be a useful addition to these systems.

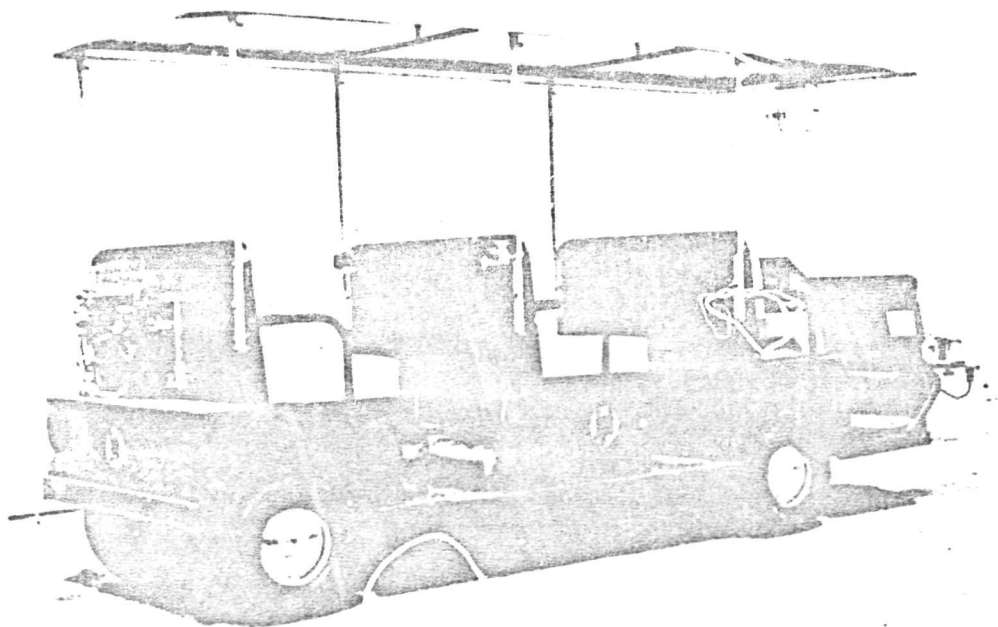
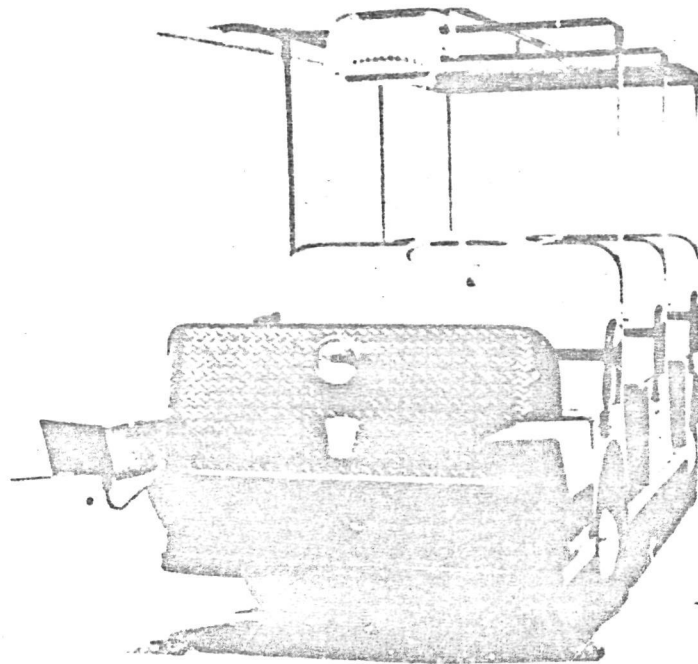
Automated Mixed Traffic Vehicle System

In the past few years, numerous efforts have been directed toward the development of the concept of small, driverless electric vehicles for mixed transit use. Interest in such vehicles stems from the fact that the relatively high costs of operating conventional mass transit vehicles, such as buses, can be directly traced to the labor costs associated with the driver. These costs limit the ability of conventional public transit to serve many areas characterized by low trip volumes and short trip distances. Although AGT systems such as those in Morgantown, West Virginia, and at the Tampa and Dallas/Fort Worth airports can eliminate most of the labor costs associated with operation, the expensive elevated or protected-at-grade exclusive guideways required by AGT systems have limited their application to major activity centers. A need was thus perceived for a less capital-intensive automated vehicle mode that could utilize existing rights-of-way with relatively minor changes. The system also needed to

TABLE 1
DOMESTIC ACT SYSTEMS

System	Manufacturer	Class	Vehicle Dimensions			Empty Weight (kg)	Number of Seats	Number of Standees	Total Vehicle Capacity	Line Speed (mph)	Minimum Headway (s)	Status to Date
			Length (m)	Width (m)	Height (m)							
AIRTRANS	LTV	CRT	6.40	2.14	3.05	6,150	16	24	40	27	18	20.92 lane kilometers, 50 stations, 68 vehicles, 201 at grade, 801 elevated, grid system with 17 intersecting routes
Aerial Transit System	Pullman Stamwood	PRT	3.66	1.48	1.59	2,177	6	0	6	32	8	Two full-scale test vehicles on 0.55-km test track
Bradley Field	Ford	SLT	7.53	2.04	2.65	6,486	10	14	24	48	20	1.29 lane kilometers, 3 stations, 2-vehicle single-path shuttle with bypass
Quach Gardens	Westinghouse	CRT	11.06	2.99	3.35	12,020	8	92	100	48	100	2.25 lane kilometers, 2 stations, 1 vehicle in one train 601 at-grade, 401 elevated, single loop
California Expo	Universal Mobility	SLT	4.27	1.83	2.25	1,081	12	0	12	19	120	2.07 lane kilometers, 2 stations, 3 vehicles in 4 eight-car trains, single-path loop
Carowinds	Universal Mobility	SLT	4.27	1.83	2.25	1,080	12	0	12	22	112	3.71 lane kilometers, 1 station, 37 vehicles in 4 eight-car trains, single-path loop
Dashawayot	Beeble	CRT	7.01	2.04	3.29	8,165	12	20	32	60	45	Two full-scale prototype vehicles on 0.15-km test track
Duke University	OTIS-TTD	PRT	6.10	3.29	2.99	5,440	12	0	12	64	2	0.80 lane kilometers, 3 stations, 3 vehicles, 501 at grade, 501 elevated
Fairlane Shopping Center	Ford	SLT	7.53	2.04	2.65	6,486	10	14	24	48	20	0.80 lane kilometers, 2 stations, 2 vehicles
GOVET	Aerospere	PRT	3.03	1.52	1.52	816	6	0	6	64	0.25	Extensive technical and planning studies, 1/10 scale model demonstrated at 0.5-second headways
Keweenaw Park	Universal Mobility	SLT	4.27	1.83	2.25	1,085	12	0	12	16	75	1.25 lane kilometers, 2 stations, 24 vehicles in 4 six-car trains
Monet International Airport	Bahr	SLT	12.20	1.52	2.29	3,165	6	4	10	19	60	1.93 lane kilometers, 8 stations, 18 vehicles in 6 three-car trains, 1001 underground
OPPER	Boeing	PRT	4.82	2.04	2.59	4,037	12	0	12	64	3	System design study in progress
OPPET	OTIS-TTD	PRT	5.79	3.05	2.74	4,898	12	0	12	64	3	System design study in progress
OPPII	Bahr	PRT	5.94	2.23	2.44	4,554	12	0	12	64	3	System design study in progress
Jetrail	Stanley Pacific	CRT	3.66	2.23	2.23	4,037	6	4	10	24	20	2.57 lane kilometers, 3 stations, 10 vehicles
King's Dominion	Universal Mobility	SLT	4.27	1.83	2.25	1,088	12	0	12	10	210	3.38 lane kilometers, 1 station, 34 vehicles in 6 nine-car trains, 51 elevated, 931 at grade, closed loop
King's Island	Universal Mobility	SLT	4.27	1.83	2.25	1,088	12	0	12	10	180	3.72 lane kilometers, 1 station, 33 vehicles in 7 nine-car trains
Magic Mountain	Universal Mobility	SLT	4.27	1.83	2.25	1,088	12	0	12	13	60	1.29 lane kilometers, 3 stations, 36 vehicles in 6 six-car trains, closed loop
Miam' Airport	Westinghouse	CRT	11.06	2.97	3.35	12,020	0	100	100	45	85	0.80 lane kilometers, 2 stations, 4 vehicles in 2 two-car trains, 1001 elevated, shuttle
Monocab	Dahr	PRT	2.83	1.67	2.04	1,814	6	0	6	48	5	0.30-km test track with 2 prototype vehicles
Morgantown	Boeing	CRT	4.72	2.04	2.68	3,900	8	7	15	48	15	8.55 lane kilometers, 3 stations, 43 vehicles, 11mm shuttle, 801 elevated, 201 at grade
Pearl Ridge	Bahr	SLT	12.19	1.83	2.34	3,265	8	8	16	13	240	0.33 lane kilometers, 2 stations, 4 vehicles in 1 four-car train, 1001 elevated, 11mm shuttle
PET	OTIS-TTD	PRT	4.34	2.85	2.50	3,265	6	0	6	72	6	0.30 lane kilometers test track with 2 prototype vehicles
Sea-Tac	Westinghouse	RT	11.28	2.83	3.35	11,566	12	90	102	48	100	2.74 lane kilometers, 8 stations, 12 vehicles, 1001 underground, 2 loops and a shuttle
Starliner	Aldem	PRT	3.81	2.04	2.74	3,410	5	4	10	45	5	Two prototype vehicles on 0.30-km test track
Tampa Airport	Westinghouse	CRT	11.69	2.83	3.35	9,752	0	100	100	45	70	2.25 lane kilometers, 8 stations, 8 vehicles, 1001 elevated
Transit	Georgia Tech	PRT					4	0	4	24	15	Full-scale test vehicle on 0.11-km test track
Uniflo	Ferguson	CRT	3.66	1.16	1.99	952	8	0	8	32-60	3	1 lane kilometer, 3 stations, 2 vehicles, closed loop, 1001 at grade
Disney World	Madway	CRT	2.43	1.48	1.38	676	4	0	4	27	14	1.10 lane kilometers, 1 station, 150 vehicles in 30 five-car trains

Note: See Glossary for meaning of acronyms.



SOURCE: JPL

FIGURE 4. THE JPL EXPERIMENTAL VEHICLE

have the ability to pick up or discharge passengers in the same way as does a conventional transit bus, thus eliminating the need for elaborate, expensive station facilities. In addition, the vehicle(s) should be able to move at low speed, over surfaces shared by pedestrians, or (possibly) move at higher speeds on a pedestrian-free path protected by suitable side barriers. The vehicle(s) would also be able to easily move from a high-speed protected guideway to a low-speed shared running surface so as to improve average speeds. This system concept has been called the "Automated Mixed Traffic Vehicle" (AMTV) transit system by its developers at the Jet Propulsion Laboratory (JPL), Pasadena, California.

A wide selection of similar vehicles are now commercially available and operational in dozens of plants and office buildings throughout the country. These systems, if properly equipped with proximity sensors, sophisticated guidance sensors, and lateral and longitudinal control systems appear to have the capability of operating in a pedestrian environment. These vehicles now are capable of automatically following a path delineated by either a buried wire or a paint stripe; they are fitted with sensors that can detect objects in their path, as well as with braking systems tied into these sensors that will stop the vehicle before collision. Some vehicles are also programmable to stop automatically at predetermined locations for loading of cargo (or passengers).

To investigate the technical practicability of the AMTV concept, an experimental sensor and control test vehicle, shown in Figure 4, was built at JPL, utilizing existing systems and control technology. The program, funded jointly by NASA's Technology Utilization Office and DOT, went on to collect data generated by this simple prototype vehicle in operation on a test route at JPL. In addition, a preliminary effort to evaluate multiple vehicle scheduling algorithms and control schemes was carried out by JPL. These studies indicated the basic feasibility of the sensing and control techniques required for AMTV operation.

Obstacle Detector Requirements

As AGT systems are extended into urban environments, the probability that the guideways will become obstructed increases because of vandalism and trash accumulation. Serious accidents will occur unless a reliable method of detecting obstacles is developed. Laser, sonic, radar, and infrared systems have all been examined, but problems of poor coverage, false alarms, and cost have never been solved in the same unit.

In an AMTV, accurate detection of both real and potential obstacles is crucial to the vehicle's operation in mixed traffic.

The general requirements for a proposed collision avoidance system are:

- Remote detection of any obstacle larger than a brick.

- Detector response time sufficiently short to allow the vehicle to stop before collision (thought to be approximately 0.1 second).
- Completely automatic; no operator.
- Size and weight not important at the outset. A practical unit must be such a size that it can be housed inside the vehicle without the passengers' noticing it.
- Low cost; should not exceed 1% of vehicle cost (up to \$1,250 per detector unit production run cost).
- Capable of operating in the electromagnetic environment (airports, radio and television stations, power transmission lines and power plants) found in large cities.
- Range of 50 feet for maximum speeds of 30 mph.
- Ability to "see" around corners.
- Minimum cross-sectional area scanned equal to cross-section of vehicle.
- Minimize false alarms due to weather (snow, rain, fog).
- In AMTV use, the ability to detect objects outside of the guideway but on a collision course.

III CURRENTLY AVAILABLE OBSTACLE DETECTORS

Five basic types of obstacle detectors are currently in use: sonic, capacitance, infrared/optical, guided radar, and probe contact. These systems are commonly used on automated vehicles such as industrial driverless tractors, carts, and fork-trucks.

In 1954, only one company was manufacturing driverless vehicles. Currently, the following seven manufacturers are producing driverless vehicles with obstacle detectors: Barrett Electronics Corp.; the Transportation Systems Division of General Motors (GM); Control Engineering Co.; Clark Equipment Co.; Lear Siegler, Inc.; Atco, Inc.; and Mobility Systems, Inc. All the manufacturers make driverless tractors except Lear Siegler, which makes only driverless carts; Control Engineering makes both tractors and carts. SRI estimates that about 800 industrial driverless tractors installations consisting of about 2,500 tractors have been sold by these seven suppliers in the United States. An estimated 1,400 carts have been sold. Each of these manufacturers offer one or more obstacle detector systems. Those systems, along with systems currently under development, are outlined in Table 2 and detailed in the rest of this section.

Sonic Detectors

The sonic obstacle detector is one of the most common technologies used to "see" in front of a vehicle. Barrett Electronics Corp., Control Engineering Co., Clark Equipment Co., Atco, Inc., and Mobility Systems, Inc., all offer this system as an option on their driverless vehicles (see Table 2).

The sonic obstacle detection systems used on driverless tractors usually consist of either two transmitter/receiver parts or one transmitter and three receivers. The sound (32-kHz range) is transmitted in a circular cone pattern in front of the vehicle with the apex at the transmitter. Consequently, the cross-sectional area covered increases farther from the vehicle and two transmitters can cover a greater volume than one.

Most systems are designed to cover an approximately 4-foot-high cross-sectional area at about 15 feet in front of the vehicle. A single transmitter system projecting a cone with a 20° apex angle would cover a 4.7-foot-diameter circular area at 15 feet. A dual transmitter system projecting two cones, each with a 6° apex angle, covers an approximately 4- by 3-foot elliptical area at 15 feet.

The sonic systems commonly monitor two zones ahead of the vehicle. The primary zone is between about 6 feet and 15 feet ahead and the

Table 2
OBSTACLE DETECTOR SYSTEMS CURRENTLY AVAILABLE AND UNDER DEVELOPMENT

Detector type	Barrett Electronic Corp.	Currently Available Systems					Systems Under Development			
		Scientific Technology (GM)	Control Engineering Co.	Clark Equipment Co.	Leor Siegler, Inc.	Atco, Inc.	Mobility Systems, Inc.	Otis Elevator Co.	GM Transportation Systems	Queen's University
Range	Sonic	Infrared/optical	Sonic	Sonic	Capacitance	Sonic	Sonic	Sonic	Infrared/optical	Guided radar
Primary zone (ft)	12-20	20-25	15	9-10	1-5	10-15*	10	10	5	Section monitoring of 1 mile
Secondary zone (ft)	8	20	6	7	None	6*	0.5	5	None	
Vehicle description	Tow-tractor (Caldwell-Matic)	Obstacle detector only. Supplier to GM LPM-1.	Tow-tractor (Pruntnow)	Tow-tractor (driverless tractor)	Self-propelled platform (Multimobile)	Tow-tractor	Self-propelled platform (Electrote)	Tow-tractor AMV (south course shuttle)	Self-propelled platform (electric pedestrian mover)	Obstacle detector only. Used as intrusion detector.

* SPI estimate.

† Four transmitters and three receivers.

‡ Custom designed for specific equipment.

secondary zone is from the vehicle out to about 6 feet ahead. When objects are detected in the primary zone, the vehicle is programmed to coast or to slow to half speed; when objects are detected in the secondary zone, normal dynamic braking to stop occurs. A single 9-foot range is sometimes used. At turns, the detection range is shortened or the detector is turned off.

One driverless tractor supplier uses a 1-foot-high, 8-inch-diameter cylinder on the floor as its standard quality control test obstacle for sonic detectors. Another supplier claims to be able to detect a 1-inch cube if it is a good sound reflector (e.g., dense material) and is oriented for good reflection back to the tractor. This supplier has also found that some porous cloths (e.g., double knits), porous materials (e.g., wire mesh), or cloth with a rough surface texture (e.g., tweed) are not easily seen by the sonic detector, although it does sometimes see and stop for rain, snow, and thermal clines in the air. Consequently, objects with any of the following characteristics are difficult to see with the sonic obstacle detector: (1) smaller than 1 square inch, (2) oriented for minimal reflection back to the vehicle (e.g., a flat surface oriented with an angle of incidence greater than 135° to the transmitted sound waves), (3) made of low-density material, or (4) having a porous rough surface.

The sonic obstacle detectors have some fail-safe features. For example, with one detector the transmitter is monitored for failure but the receiver is not. All the suppliers recommended that the obstacle detectors be tested before vehicle use each day.

In the south concourse of Cleveland Hopkins International Airport, three AMTVs manufactured by Otis Elevator Company were operated on a guide-path shared with pedestrians as part of a 2-week feasibility test conducted in 1974. A standard Otis industrial tractor was adapted, and three trailers were added to carry people. An ultrasonic object detector was designed to have a range of about 50 feet and to sense an area that was close to the floor and the width of the trailer.

When the sonic object detector scanned obstacles within 10 feet, the vehicle slowed to 1 to 1.75 mph; and at 5 feet, the vehicle began to brake so as to stop no closer than 1 foot from the obstacle. No accidents or injuries occurred during the 16-day test. Otis had a uniformed man on each vehicle to stop it in case of a pending accident, but overriding the automatic control was never necessary.

The Otis obstacle detector is still considered to be "under development" and has not been made commercially available.

Although the sonic systems meet many of the AGT and AMTV criteria listed on page 13, all the devices are prone to false alarms, do not cover a sufficiently large area for vehicles traveling near 30 mph, and do not provide any warning of obstacles around corners.

Capacitance Detectors

Lear Siegler's Automated Systems Division produces an automatic mail document conveyor, Mailmobile.^(R) According to Lear Siegler:

The Mailmobile is a self-propelled, battery-driven, automatically guided office delivery vehicle. Traveling to and from a mailroom or other central facility along an invisible guidepath, Mailmobile covers a fixed 'messenger route' throughout an entire floor. It automatically stops at designated stations for pick-up and drop-off of mail.

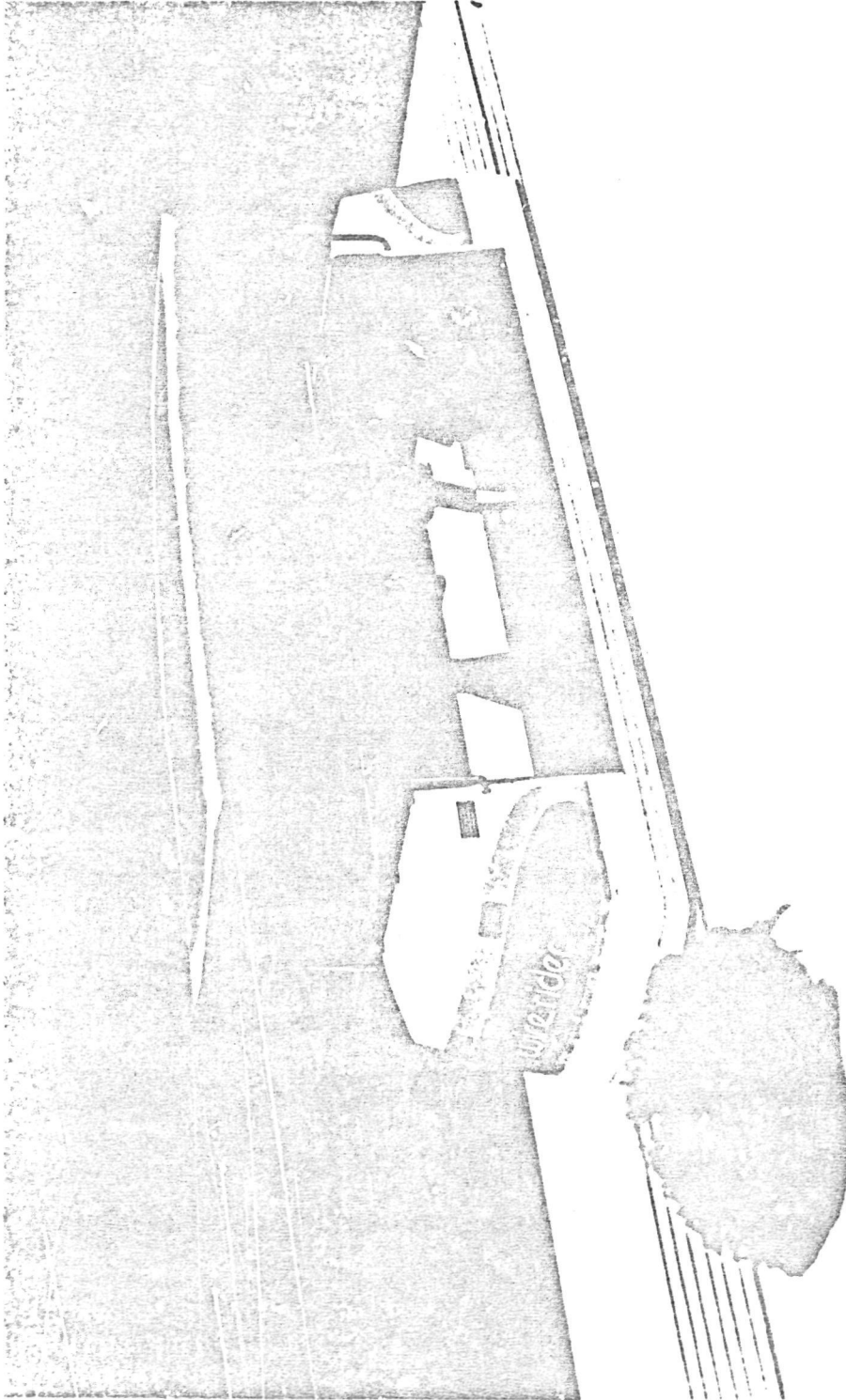
An optional, capacitance obstacle detector system is offered. In this system, a limited radio field is used to detect objects that cause a change in the shape of the field. This consists of a tuned circuit that detects the presence of objects by sensing the resulting change in capacitance between an antenna array and the chassis of the Mailmobile. The antennas have been carefully configured to provide maximum sensitivity to objects in front of the vehicle while minimizing the sensitivity to objects at the sides and on the floor. This is necessary to avoid false stops when the Mailmobile passes over metallic objects in the floor and when it traverses narrow corridors and doors where minimum clearance is required. Circuitry to inhibit the proximity detection system in response to codes adjacent to the guidepath is available at an additional cost. This prevents false stops when turning the Mailmobile in narrow hallways or passing it close to fixed objects is necessary. The sensing range of the Mailmobile is only 18 inches in front of the vehicle, making it unsuitable for AGT use.

Infrared/Optical Detectors

Starting in November 1974, the Transportation Systems Division of GM Corporation began development of a 2.2-mpa AMTV called the Electric Pedestrian Mover (EPM). The EPM is a self-propelled platform following a buried guide wire.

Two obstacle detectors were developed for this system. One, made by Scientific-Technology, Inc. (Mountain View, California), is currently available. The other, by GM, is still under development. The Scientific Technology detector used on EPM-1 (the first of two prototype EPMs) is a series of four infrared transmitters and three receivers located across the front of the vehicle just above the bumper. The range of the detectors is between 10 and 25 feet. GM identified two problems with this system: (1) sunlight could swamp the photodetector, making the system inoperable, and (2) it could not detect certain colors (e.g., gray) and textures (e.g., corduroy).

Realizing that the noncontact obstacle detector performance was the key to the function of the EPM, GM rejected the Scientific Technology detector and started development of its own infrared detector for use on EPM-2, shown in Figure 5.



Source: General Motors Corp.

FIGURE 5. EPM-2, THE PROTOTYPE VEHICLE

Using a transmitter mounted low on each side of the front of the vehicle, two receivers mounted above it, and a special lens developed by GM engineers, GM was able to cover an area equal to the front cross-section of EPM-2 out to 5 feet ahead. However, one conical volume with its base at the vehicle and its apex less than 2 feet in front of the vehicle was a blind area to the GM infrared detector. The lens technology used was a key factor in the effectiveness of the detector in laboratory tests.

Because EPM-2 was not completed, the GM detector was not tested on the vehicle in service. Results of laboratory tests, however, made GM engineers confident that it would give a much better performance than the detector on EPM-1.

GM also considered scanning sensors--sensors that would rotate into the direction of turns--and an array of sensors, some of which would be aimed into turns and others that would be aimed straight ahead.

Although an infrared/optical obstacle detector shows great promise with further development, problems of false alarms, weather, and "seeing around corners" are still unresolved. However, this technology was selected for further development in the NASA/JPL AMTV program. That work is discussed in Section IV.

Guided Radar Detectors

Guided radar is a relatively new field in which radar signals are propagated along a new medium, namely, so-called leaky coaxial cables. The zone of detection is defined by the placement of two leaky cables side by side but is essentially longitudinal. Typically, the zone may be up to 1 mile long and a few feet wide, a feature that is particularly useful for the railroad and automated transit vehicle environment.

The technique was developed under a contract from the Canadian Institute of Guided Ground Transport at Queen's University during a study of the propagation characteristics of the leaky cable medium. Applying that technique, Computing Devices Company, Ottawa, markets a commercial product that is designed to provide perimeter surveillance as an intrusion detection system. Prototype systems have been installed as line sensors for the U.S. military and the Canadian Penitentiary Service and have undergone more than 12 months of testing.

Concurrent with this development program, a sophisticated guided radar facility, the Guided Radar Information Processing System (GRIPS), has been installed at Queen's to be used as a scientific tool in the investigation of other applications of the technique and for further fundamental studies of the propagation medium. The sensor (two leaky cables) can be installed in whatever configuration is appropriate, and the processing system can be programmed to perform analysis and signal processing.

For this project, a small section of railroad track was installed and two cables in the sensor were placed at various positions parallel to the rails. By monitoring the influences of targets and comparing these influences to those created by environmental changes, Queen's researchers found the technique to be effective.

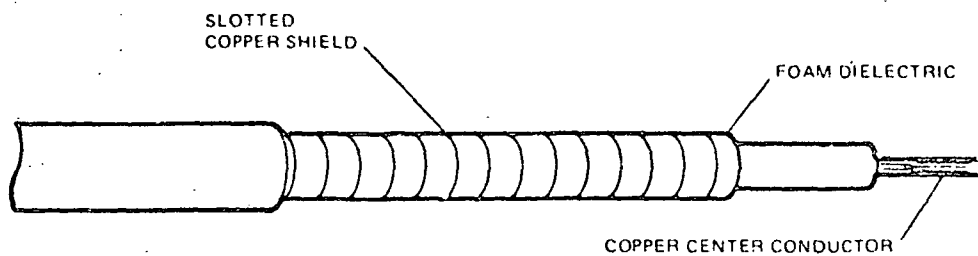
This obstacle detection system utilizes the properties of leaky coaxial cables to establish an electromagnetic field in essentially a longitudinal zone of detection. Leaky cables were first developed for use in communication systems and many varieties are now available. Although the construction technique varies according to cable type, each cable shares the same essential characteristic. Figure 6 shows a typical method of fabrication, in which a portion of the outer conductor of a common coaxial cable is removed in a series of regularly spaced slots. The break in the outer conductor allows some of the electromagnetic energy traveling within the cable to "leak out" and travel as a surface wave within the vicinity of the sensor (the other cable).

Many cable types have been tested at Queen's over the past few years. The Radiax RX4-3 appears to be the most suitable type available for use on the railroads and automated transit vehicles. Accordingly, in all tests conducted for this project that cable type was used as the detection sensor.

Figure 7 illustrates the guided radar concept. A pair of leaky cables spaced a few feet apart and running parallel to each other comprise the guideway or sensor. A pulse of radio frequency energy is injected into one of the two cables (called the transmit cable); some of the energy leaks out and establishes some form of external field along its length. A portion of this field is coupled into the receiving cable and is subsequently demodulated in the synchronous detector. The detected signal, called the cable profile for convenience, is shown in Figure 7 as waveform S_1 . An obstacle or target, be it dielectric or metallic, entering the guideway causes a slight localized perturbation in the profile at a point in time corresponding to the target's location. This is illustrated in Figure 7 as detected waveform S_2 . The return cable profiles, S_1 and S_2 , are sampled through a moveable window, digitized and separated into a number of range-cells, each range-cell representing a certain location along the cable (illustrated in waveforms S_1' and S_2' of Figure 7). The processor performs, on a cell-by-cell basis, the removal of the stationary cable profile S_1' by simply subtracting it from the nonstationary return signal S_2' . The result is the "Target Response" shown at the bottom of Figure 7.

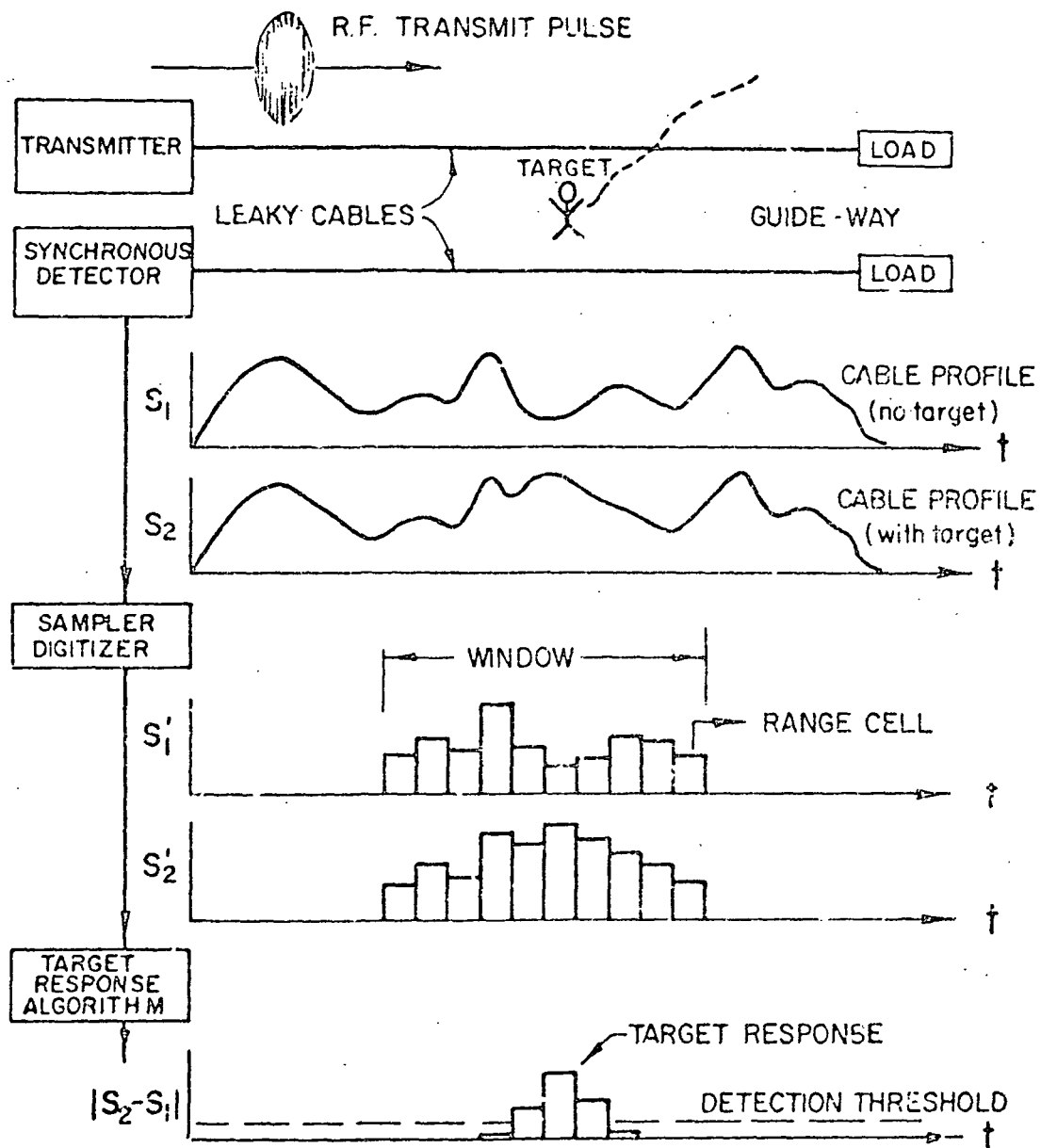
For obstacle detection (such as rock and slide detection for rail safety or perimeter surveillance for security applications), a threshold is set so that an alarm is produced whenever a suitable target comes within the vicinity of the guideway. Thus, detection is said to have occurred whenever a generated target response has exceeded this threshold, as shown in the final diagram of Figure 7.

This system provides both detection and location of an obstacle along the track, and the location accuracy is determined by the width of the



SOURCE: Queen's University. Guided Radar for Railway Obstacle Detection, Report prepared for the Canadian Institute of Guided Ground Transport, Project No. 1.33.77, Kingston, Ontario, 30 November 1977, p. 2-2.

FIGURE 6. DIAGRAM OF A RADIAX RX4-3 LEAKY CABLE



SOURCE: Queen's University report, p. 2-3.

FIGURE 7. DESCRIPTION OF THE GUIDED RADAR CONCEPT

transmit pulse. As the pulse is widened, detection is still possible but location accuracy is reduced.

A simplified system can be considered in which the transmit pulse is extended until its waveform is continuous. In this, the continuous wave mode, the transmit-and-receive equipment is greatly simplified and the net power to the cables is increased. Consequently, although location of the obstacle is not possible, the actual detection probability of the obstacle is greatly enhanced.

Queen's University concluded that a guided radar system can detect rocks greater than about 10 inches anywhere within the railroad clearance lines. The detection zone is well contained in that it extends to less than 1 foot beyond each cable sensor and is only a few feet high. Sensitivity varies with cable position; the system detects smaller rocks close to the cables and may or may not have a uniform detection zone, depending on the configuration of the sensor.

The system appears to have many advantages appropriate to the AGT, AMTV, and railroad environment--for example, low false alarm rate, potential for all-weather operation, fail-safe features--but as with all sensors, it may not be totally foolproof for every application. Most likely, such a system might be used in parallel with some other detection scheme to fill in any missing capability.

Probe Contact Detectors

All the driverless vehicles reviewed have a mechanical bumper obstacle detector that requires contact with the obstacle for detection. These probes or bumpers typically extend to the front 1 to 2 feet and 6 inches to the sides of the vehicle. Any contact with these surfaces produces a full emergency stop. Pressures between 8 and 16 ounces are required to activate.

The mechanical bumpers are designed to be fail-safe. Failure of any active components mounted on the bumper or of electrical connections to the tractor that result in a short circuit can produce the same short circuit signal as caused by a normal obstacle detection.

IV NASA TECHNOLOGY

Over the past 10 years, NASA has directed its efforts in developing obstacle detection systems toward the design, construction, and evaluation of a planetary rover concept; the objective has been to achieve exceptional mobility and maneuverability. During this period, an investigation was undertaken of methods for sensing and interpreting the terrain for purposes of path selection and obstacle detection. The NASA technologies and hardware that were developed through these efforts are summarized in Table 3 and detailed in this section.

Table 3

OBSTACLE DETECTOR SYSTEMS DEVELOPED BY NASA

Detector Type	Range (ft)		Vehicle Description	Developer
	Primary Zone	Secondary Zone		
Infrared/optical	25	8	Self-propelled platform (AMTV)	JPL
Laser	25	--	Obstacle detector for Mars rover	JPL
Laser	25	90	obstacle detector for Mars rover	Rensselaer Polytechnic Institute

Short-Range Obstacle Detector (NASA Tech Brief 74B10101)

In 1974, Kuriger et al Caltech/JPL developed a short-range laser obstacle detector designed to help a slow-moving vehicle explore the surface of Mars. This system automatically diverts the vehicle from obstacles as small as 18 inches in diameter that are in its path.

The detector comprises an injection laser operating in the pulse time-delay measurement, or radar, mode. It is capable of scanning an area extending from a few feet to approximately 100 feet. Used as a Mars excursion controller, the detector generated command signals to divert the vehicle from collision.

Figure 8 shows the major components of the detector system. The transmitter portion of the range finder consists of an array of five gallium-arsenide laser diodes, each equipped with its own driving circuit. Each diode has a typical output of 13 W and an emitting area on the order of 1 by 90 inches. The diffraction-limited beam spread for the laser itself is on the order of 0.3 rad. Because the target area is illuminated with a beam of the smallest possible diameter, a collimating lens is incorporated to minimize target-induced pulse spreading and split returns.

The beam is swept by the vertical scan at an angular rate of 68.5 rad/s; thus, when a transmitter pulse repetition rate of 10 kHz is used, the terrain is sampled at 2-foot intervals at the midrange distance of 45 feet for the vehicle on a level terrain. Because only one laser diode is operated on each vertical scan, the entire field is scanned once each 0.2 second, a time that is sufficiently short so that vehicle pitching and rolling should only occasionally interfere with the scan.

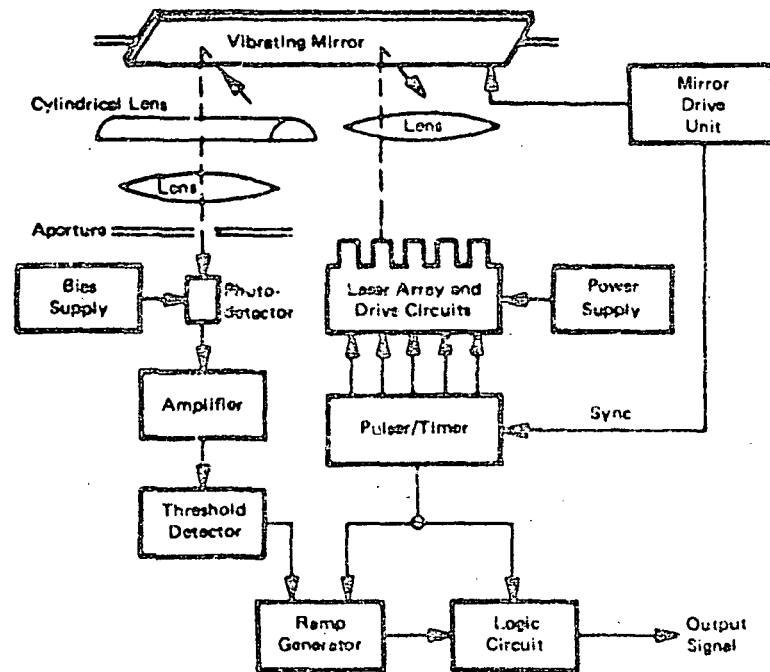
A 25-mm f/3.2 simple lens is used to collimate at least 80% of the radiation emitted by any one of the five diodes and to project it onto a spot never larger than 4 inches in diameter for ranges up to 100 feet. The diodes are spaced at 1/4-inch intervals along the lens focal plane to achieve the required scan coverage. The pulser/timer sequentially operates one laser of the array on each elevation sweep and fires the laser diodes at a 10-kHz rate with a pulse duration of about 5 ns.

The receiver portion of the range finder contains collecting optics, a photodetector, an amplifier, and a threshold detector. The optics consist of a cylindrical lens followed by a 1-inch diameter simple lens to produce a receiver beam width of 3 mrad in elevation and 0.4 rad in azimuth. This particular beam shape includes all the azimuthal area in its field of view illuminated by the transmitter, but it is otherwise minimized to reduce the amount of background solar radiation intercepted.

The optical system also contains a 5.0-nm pass-band optical filter to discriminate further against background radiation. The optical band width is made as narrow as laser characteristics permit. Room temperature gallium-arsenide injection lasers emit a nominal wavelength of 902.0 nm, with an output wavelength spread on the order of 10 angstroms caused by multimoding and by heating within the duration of a pulse.

The receiver aperture is selected to be small but comparable to the area required for the transmitter optics. Sensing is provided by avalanche photodiodes operated at a gain between 100 and 200 to yield an adequate signal-to-noise ratio at a 100-foot range.

At the nominal condition of level vehicle attitude, a vehicle traveling at a velocity of 6 inches/second (0.3 mph) will detect a given obstacle 900 times in the 5- to 100-foot search range. This redundancy is somewhat reduced when the vehicle is pitching but is still sufficient to prevent false alarms; that is, an obstacle is detected several times in succession before the sensor signals its presence.



SOURCE: NASA Technical Brief B74-10101, August 1974

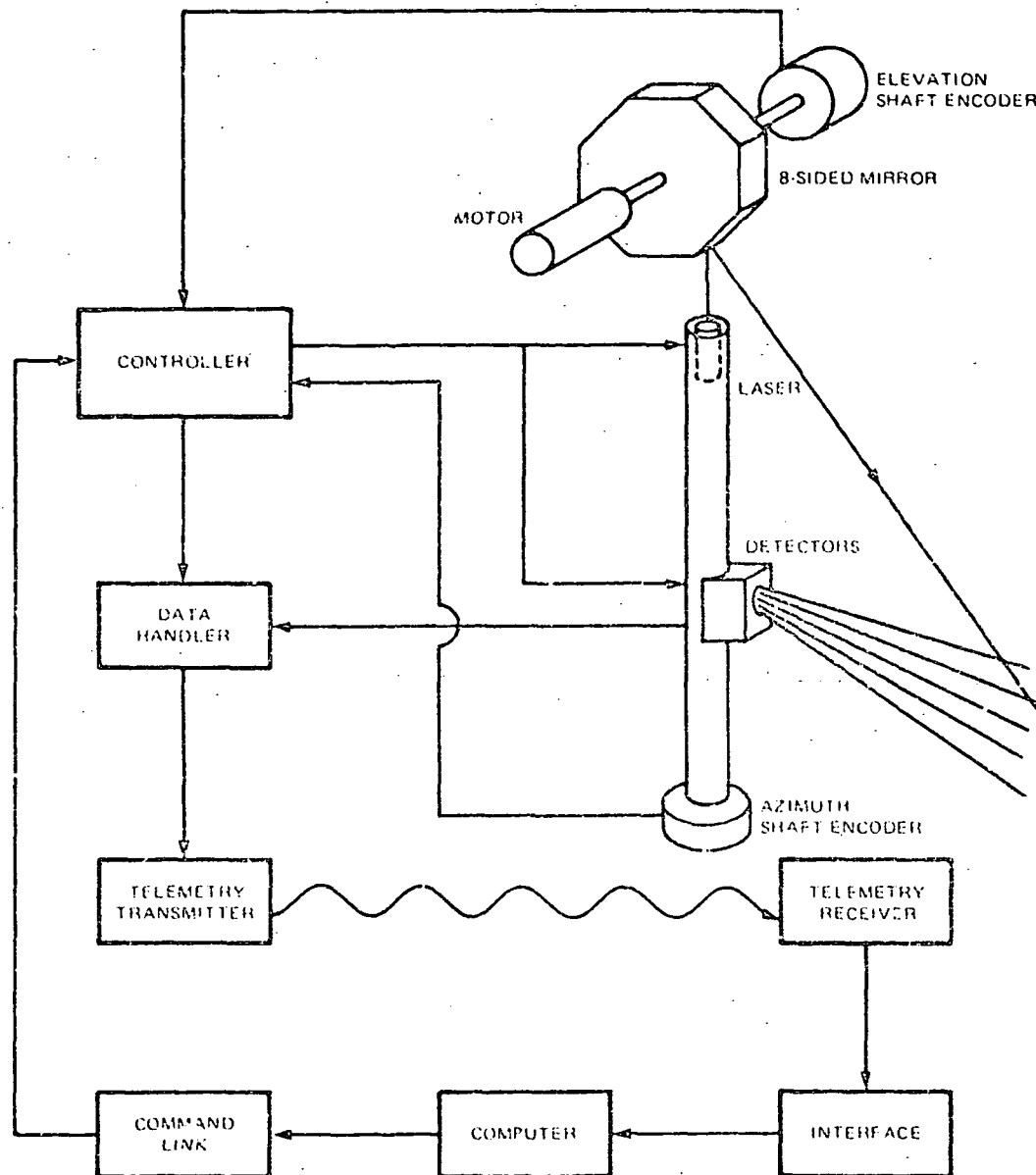
FIGURE 8. SHORT-RANGE OBSTACLE DETECTION SYSTEM

Although the range and tight field width of this detector make it suitable for use on AGT and AMTV obstacles of less than 18 inches in diameter, it could still pose a threat to an oncoming vehicle. The classical problem of seeing around corners is also unresolved in this device.

Hazard Detection System for Autonomous Control of Roving Vehicles for Unmanned Exploration of the Planets (NASA Grant Nsg-7369)

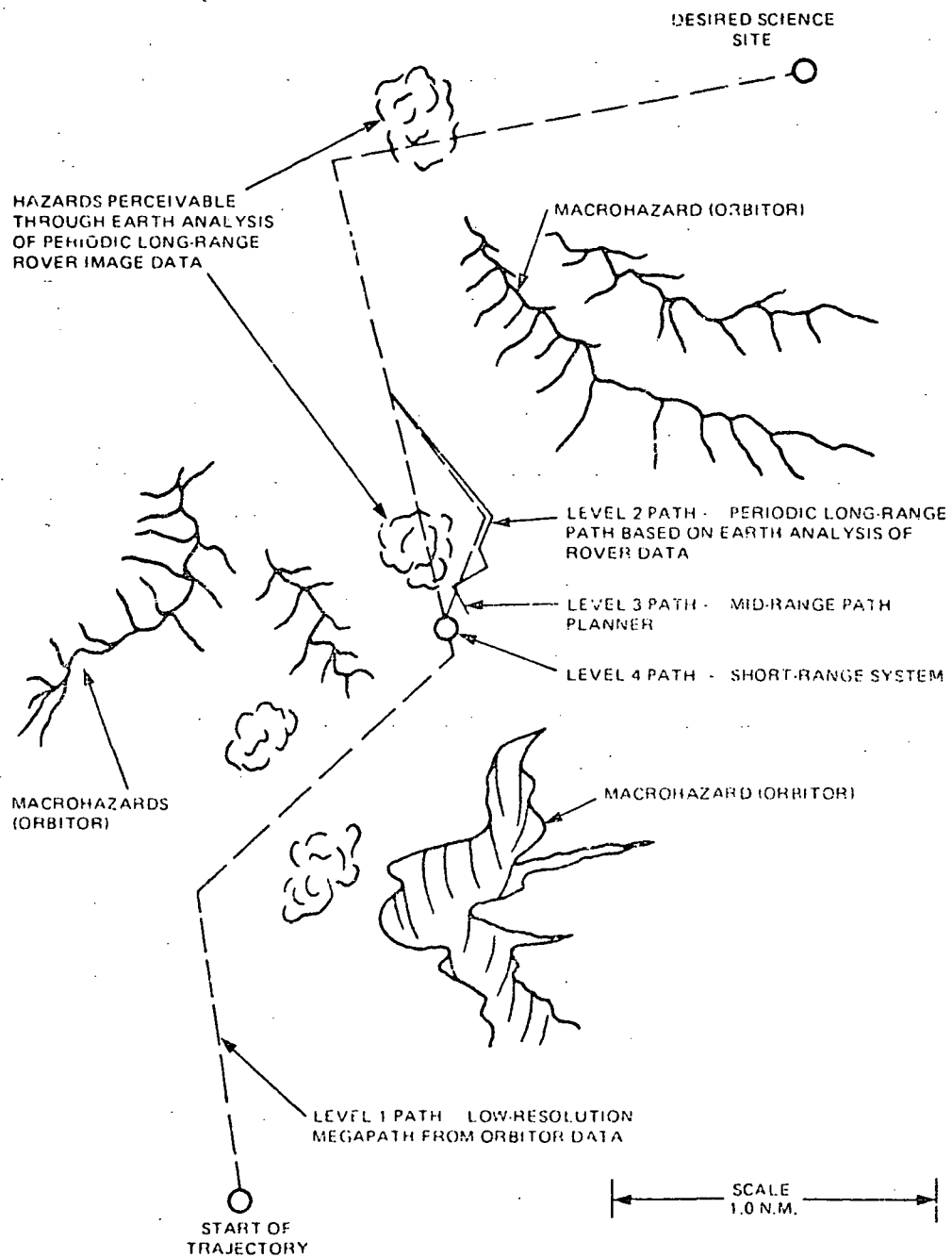
Rensselaer Polytechnic Institute (Troy, New York) became involved in the Mars Rover Project in 1972 with a NASA grant. The principal goal of the project was to develop a test vehicle that was capable of autonomous roving--that is, of obstacle detection and avoidance under closed-loop computer control. The vehicle was to gather information with some type of "vision" system and return it along with vehicle state data via telemetry. The obstacle detection system was chosen to use a "laser triangulation" scheme, depicted in Figure 9. A laser is at the top of a vertical mast at the front end of the vehicle and points downward toward the ground. The mast rotates around its long axis, causing the laser spot on the ground to describe an arc of about 140° in the azimuth direction in front of the vehicle. Mounted at a lower point on the mast is a detector with a narrow field of view (approximately 3°) aimed at an angle relative to the mast toward the ground such that on flat terrain it will always see the laser spot; but when an obstacle of appreciable size (approximately 10 inches) intercepts the laser beam, the laser spot will be outside the field of view of the detector, and the obstacle is detected. As the mast rotates, the laser is fired at 1,024 different locations. Thus, triangulation occurs in the plane that contains the vertical mast. The angle the laser makes with the mast and the angle at which the receiver is pointed are fixed. The system yields the information "direction blocked" or "direction open" for the 1,024 directions in front of the vehicle. Using this system, autonomous roving was achieved and tested under various conditions and with varying degrees of success, as shown in Figure 10.

To simulate many lasers at different pointing angles, the system uses a single laser that is reflected by an eight-sided rotating mirror at the top of the mast. With eight sides, the laser can be pointed at any desired angle within a 90° field. The laser has the capability of 10 kHz firing rate. Speeds of this order are dictated by geometry and desired system performance. Finally the system has a multielement detector. Either a 20-element photo diode array or a 1,024 element CCD linear array will be used, although neither is complete at this time. With this system, the height of terrain can be computed for up to 1,024 points around the vehicle. This device meets many of the AGT and AMTV detector requirements, and detection of obstacles of approximately 10 inches in diameter comes close to the limits set. However, the problem of seeing around corners still exists, and high cost also limits use of this device.



SOURCE: J. Craig and S. Yerazunis, NF8 29132

FIGURE 9. ELEVATION SCANNING CONCEPT



SOURCE: Craig and Yerazunis, NFB-29132

FIGURE 10. CONCEPTUAL MULTI-LEVEL GUIDANCE SYSTEM FOR AN UNMANNED PLANETARY ROVER

Automated Mixed Traffic Vehicle Obstacle Detector (Jet Propulsion Laboratory)

A feasibility demonstration of an AMTV, using what was basically a breadboard vehicle, was conducted at JPL during early 1976. The program was funded jointly by NASA's Technology Utilization Office* and the Technology Development and Deployment Division of UMTA. The sensors used for collision avoidance were developed at JPL and were derived from earlier work on sensing for remote manipulation applications.†

Although a number of other sensing concepts are possible, optical sensors have been used on the JPL AMTV for headway sensing. The system consists of an array of four 25-foot sensors, which together generate a beam about 6 inches thick vertically and somewhat wider than the vehicle, and two similar but smaller fan beam secondary 8-foot sensors. These are simple fixed devices without scanning elements or precision optics. This set of optical sensors provide overlapping coverage for basic straight-ahead collision avoidance.

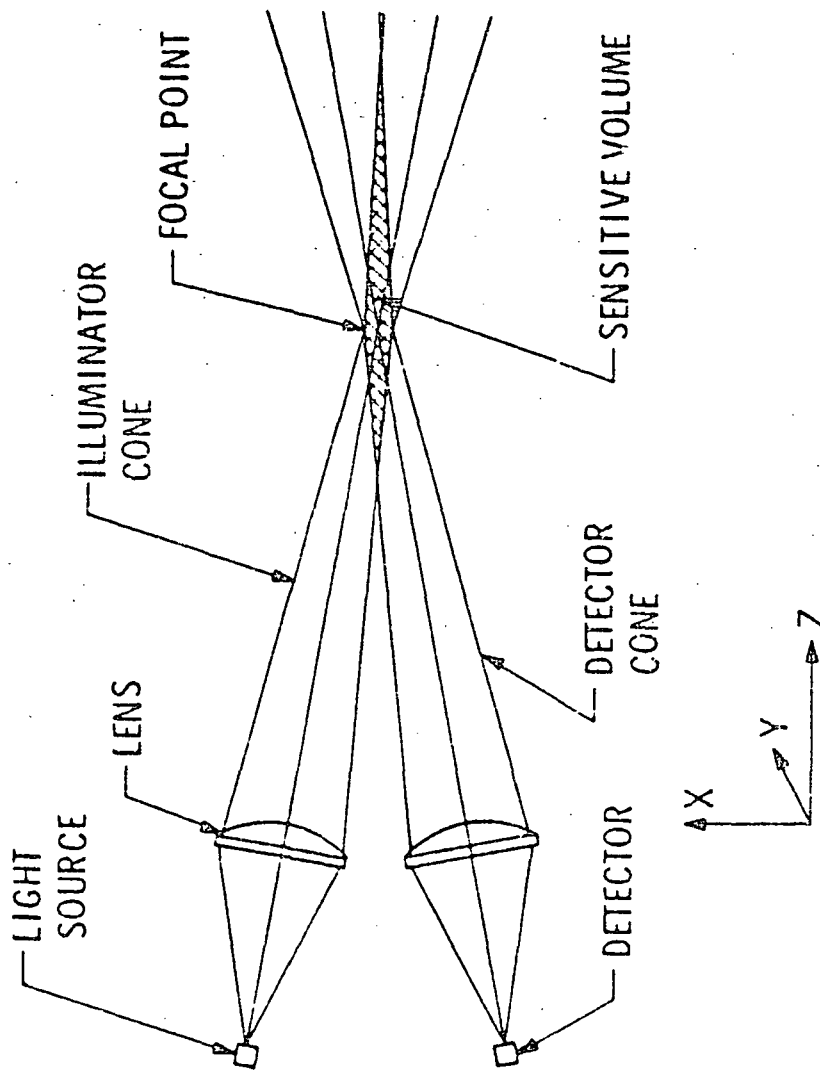
Figure 11 illustrates the operating principle of the headway sensors. The light source is a gallium-arsenide LED emitting at a wavelength of 0.94 μ . A silicon solid-state detector is used to sense any light reflected back by an object in the carefully defined light beam. Only objects in the overlapping volume of the transmitted light beam and the detector field of view will be detected. Both a pulsed LED with electronic phase detection and an appropriate narrow-band optical filter are used to discriminate against sunlight and other unwanted background light.

Figure 12 shows the desired overall beam profile. Two beam profiles are shown, a 25-foot primary beam and a 5-foot secondary beam. The profile indicates the boundary of the region within which a minimum-area target will be detected. The sensitive region corresponds to the shaded overlap of the two beams. In the fan-beam configuration, the cylindrical lens spreads the beam horizontally, perpendicular to the plane shown in Figure 11.

As Figure 13 shows, the control logic is a very simple on/off scheme. It appears to be adequate for a 7-mph operation, for which a comfortable stopping distance is 15 feet, but it would need to be more sophisticated for vehicles traveling at speeds of 15 mph or greater. All changes in

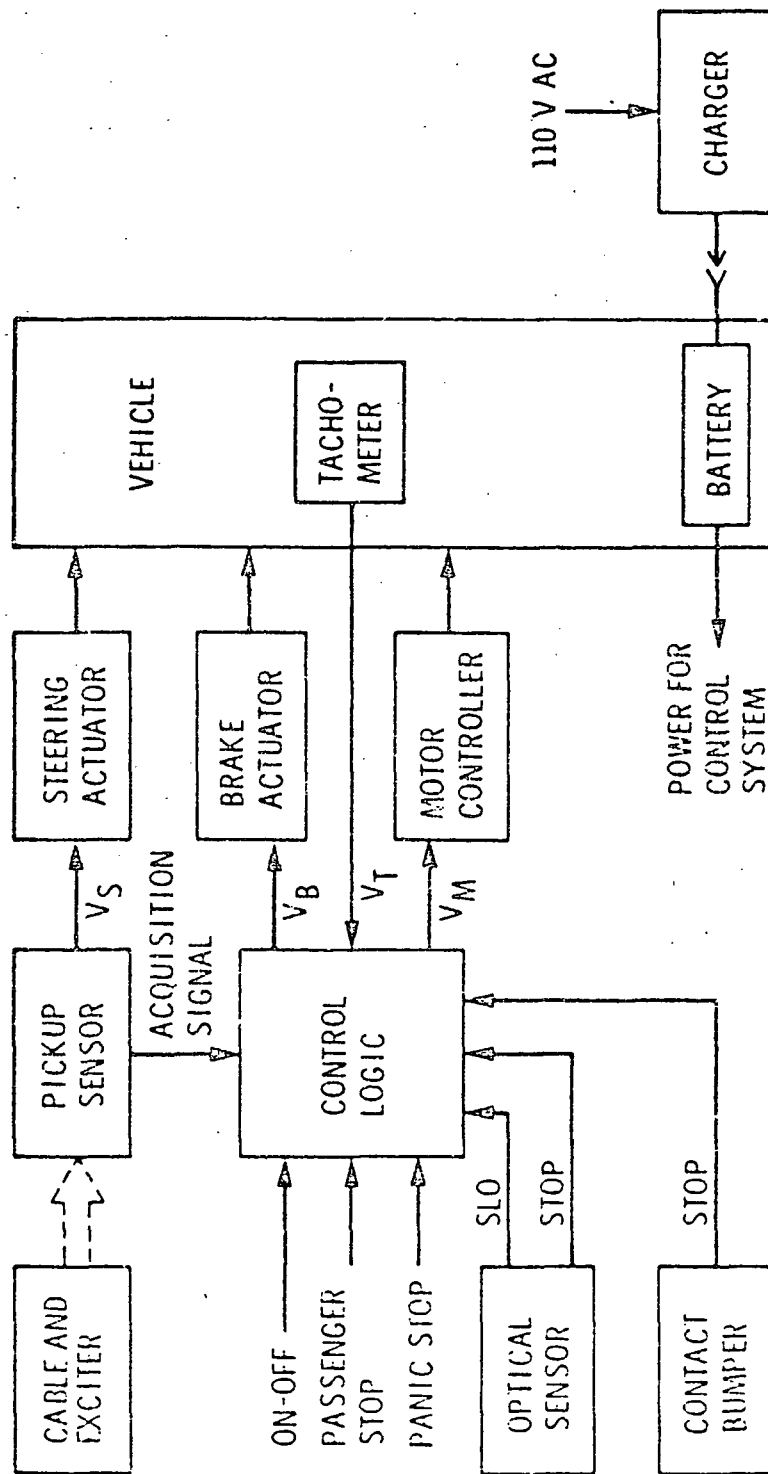
* Now named Terrestrial Applications Branch, Technology Transfer Division.

† J. Rodwell, "Driverless Bus Nears Reality," Commercial Motor, June 14, 1974; S. Penoyre, private communication, Transport and Road Research Laboratory, Crowthorne, Berks, U.K., February 1975, and A. R. Johnston, "Proximity Sensor Technology for Manipulator Effectors," Mechanism and Machine Theory, 95, 1977, 12.



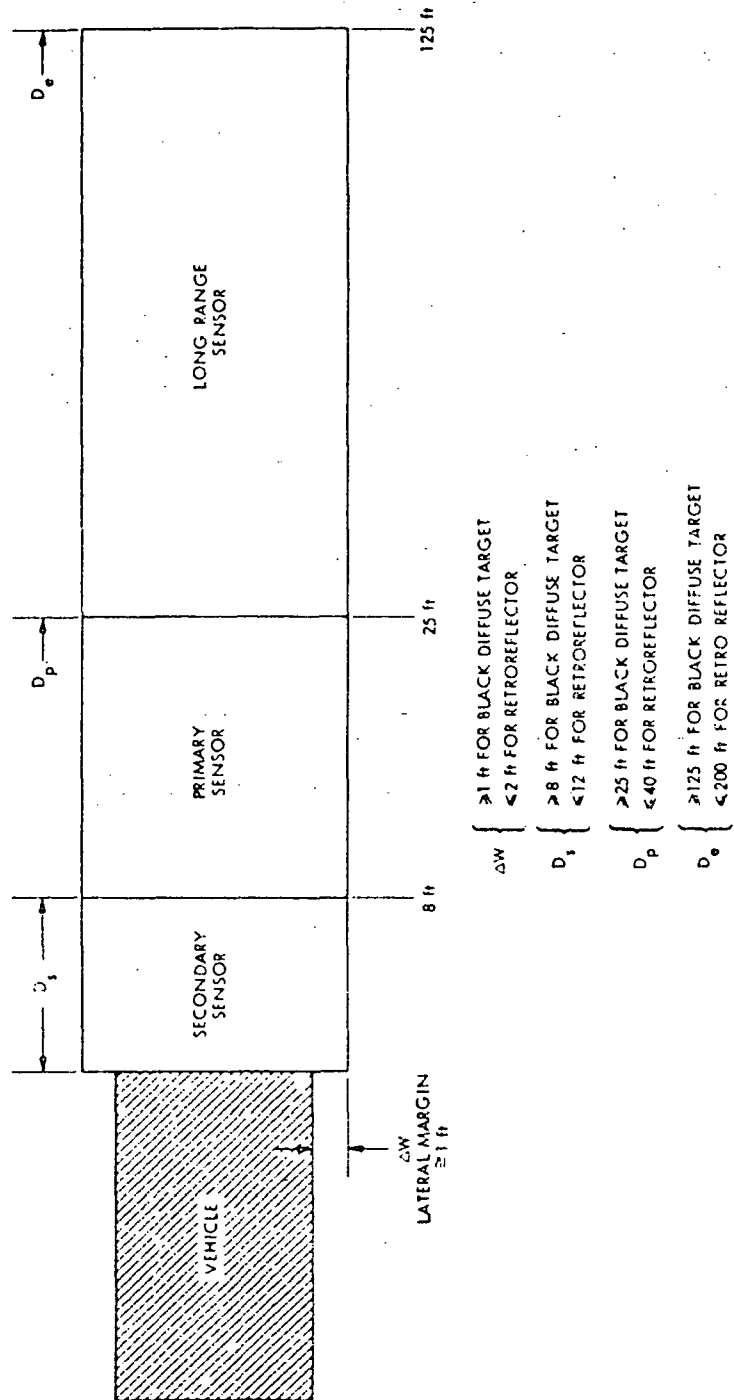
SOURCE: JPL

FIGURE 11. SKETCH SHOWING PRINCIPLE OF OPERATION OF OPTICAL HEADWAY SENSORS



SOURCE JPL

FIGURE 12. AUTOMATED MIXED TRAFFIC VEHICLE BLOCK DIAGRAM



SOURCE: JPL

FIGURE 13. OPTICAL HEADWAY SENSOR COVERAGE DIAGRAM

speed are acceleration and jerk rate limited by a program internal to the control logic. A flexible "whisker pole" bumper also contains microswitches that command the emergency stop if the bumper is touched. The diagram in Figure 12 illustrates ideal sensing patterns for each of the sensor elements; the rectangular areas shown for each sensor element indicate the area within which the sensor must detect an obstacle. Acceptable margins for each area are also indicated. The actual individual detector beam areas are elliptical, as Figure 14 indicates, so design compromises must be made to approach the ideal field pattern.

The 1-foot lateral margin requirement (ΔW) shown in Figure 12 is defined such that the sensing system will detect low-reflectivity targets from 1 foot left of the vehicle to 1 foot right of the vehicle and will be insensitive, or blind, to retroreflective surfaces that are at least 2 feet away from either side of the vehicle.

Although the present sensing performance has been adequate for the breadboard feasibility demonstration, it would not be adequate in an AGT or AMTV operational situation. The signal-to-noise ratio for a black target is marginal, and the interrelated time constant of the sensor outputs (0.5 second) is excessive. Beam definition, both laterally and down-track, also needs improvement.

Fabrication and evaluation of an improved set of sensors is planned. This set is an array of seven sensor elements, each element performing both the primary and secondary sensor function. One element of this set has been built and laboratory tested. Its beam definition has been found to be satisfactory, and a sufficient signal-to-noise ratio to obtain a 0.1 second time response has been obtained. Evaluation of this system will continue with tests on the present vehicle.

Additional specific developments that must be made to improve the various sensors are described below.

Long-Range (20 mph) Sensor

Sensing elements to detect vehicles or other large objects at a distance of 125 feet must be developed for vehicle operation at 20 mph to allow the vehicle to make a smooth stop in an AMTV environment. AGTs on dedicated guideways require only emergency stop capabilities. No past work has been specifically aimed at these requirements, so this is a new development task. Light source power constraints will limit the capability to detect small black targets using an extension of the present primary sensor approach. However, reliable detection of other AMTVs or automobiles in a guideway is straightforward. Therefore, reasonable performance goals for a development task are to achieve:

- Reliable detection and emergency stop for a pedestrian or object of similar size in a guideway.
- Reliable detection for a programmed stop (normal deceleration) for another AMTV or automobile in the guideway.

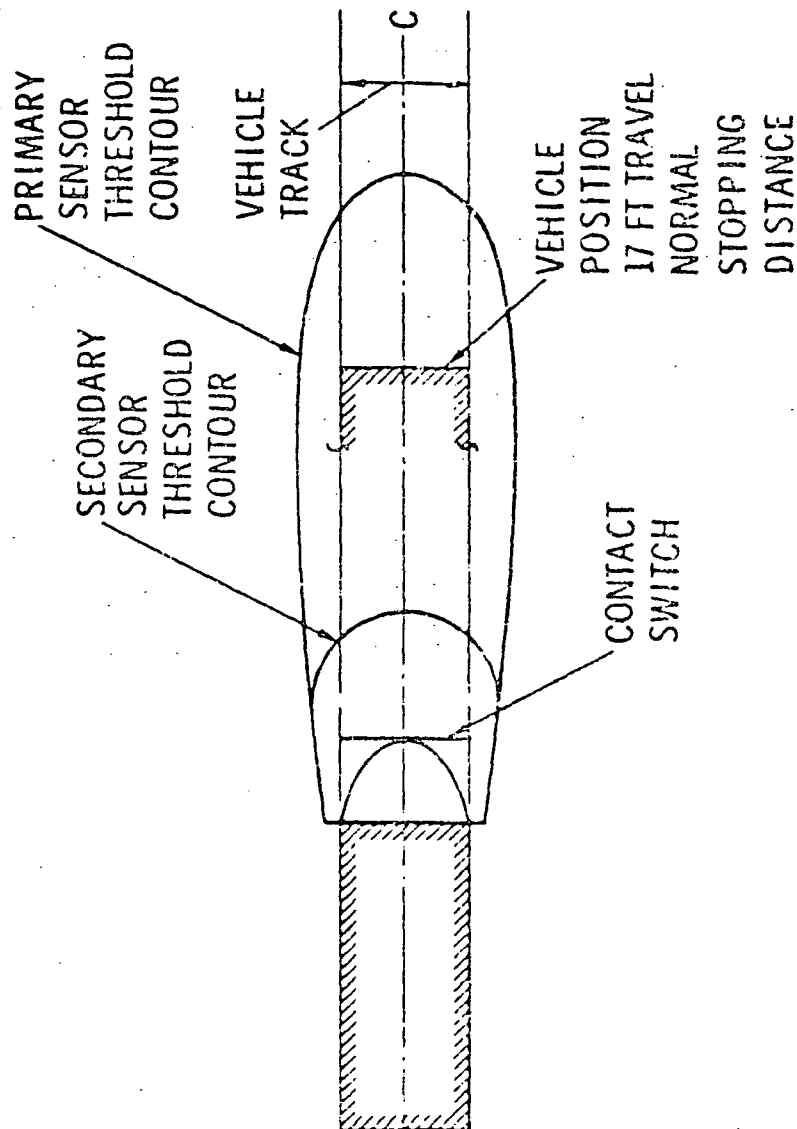


FIGURE 14. SENSOR THRESHOLD CONTOUR

SOURCE: JPL

In this context, "emergency stop" denotes stopping the vehicle using maximum braking effort. Stopping in this mode would be an abnormal event because the guideway security would have been violated to necessitate the stop.

Other improvements required to achieve these goals are optimized signal-to-noise design of the sensors and improved optical design for beam definition at a 125-foot range.

Primary Sensors

The primary sensors carry the main headway sensing burden. They must operate without the degree of control over the operational environment that can be provided by the 20-mph guideway. Except for the different range requirements, the two sensor types are functionally equivalent.

The following items should receive attention. The specific ideas presented apply to both the primary and the long-range (20-mph) sensor systems.

Detector Noise and Response Time Optimization--Detection of a black target at 25 feet and discrimination against a distant, fully sunlit, white background are conflicting requirements. Optimization of the detector channel for best signal-to-noise performance is needed. Detector response time is inherently coupled with noise and should be considered as a part of the trade-off. A detector response time of 0.1 second is believed to be necessary to obtain an overall vehicle response time of 0.2 second--a value that approximates the expected response time of a human driver.

Beam Definition--The sensed area must be precisely defined laterally to allow an AMTV unimpeded passing of parked cars. The need for good beam definition arises because of the extreme difference in reflectivity between a black diffuse target and a retroreflective lens such as an automobile taillight or reflector. The sensor beam will always be larger for retroreflective targets because much more light is returned to the detector by a retroreflector.

Two approaches are possible for achieving the required beam definition. The one to be investigated next involves the use of an array of several sensing elements, each one a narrow, well-defined (6 inches laterally) beam. The other entails the development of special (perhaps aspheric) optics designed to cover the required area with one or two sensor packages. A cost trade-off exists between the two approaches: More costly optics are used in one case whereas many simple sensing elements are used in the other.

Vertical Extension of Headway Sensing Area--The present sensors cover only a plane near the road surface (1 foot high). Ultimately, extension to cover the total height of the vehicle will be needed or,

because the probability of encountering an overhead obstacle is low; such an occurrence may be treated as an emergency stop situation covered by a bumper switch.

Sensor Pointing During Turns--The most frequently encountered shortcoming of the simple straight-ahead sensor beam of the breadboard AMTV involved lateral coverage during turns. With a sensor beam 1 foot wider than the vehicle and extending 25 feet ahead, calculations indicate that a turn with a radius of 300 feet or less will compromise the headway protection on the inside of the turn. Possible solutions are coupling of the sensor beam with the steering angle or developing some means of switching in or out special sensor elements directed at a slight angle to the vehicle centerline. In addition, a means to signal the vehicle in advance of a turn appears to be needed, not only for lateral sensor coverage, but possibly also for speed control. In developing a simple mechanization of turn-coupled headway sensing, limiting the route turn radii to one or a few standardized values would be advantageous.

Secondary Sensors

Except for beam definition, the secondary sensors used on the JPL experimental vehicle provided satisfactory performance. However, in addition to the straight-ahead sensing requirement, the secondary sensing system of an operational AMTV must also provide warning of collision during a minimum radius turn (U-turn); that function was not incorporated in the JPL experimental AMTV. Such a turn is performed at low speed and is a separate problem from the cruise-speed turn problem discussed above. In a U-turn, the velocity vector of the front of the vehicle is rotated by an angle of 45° or more relative to the centerline. Suitable short-range sensors looking to the side (and even toward the rear for passing traffic) are needed and can be incorporated as part of the secondary sensing channel. These can be activated by steering angle, but road-fixed signals to anticipate the U-turn may also be desirable.

V. COST ANALYSIS

The obstacle detector costs shown in Table 4 range from a low of \$850 for the Scientific Technology Infrared device to a high of \$5,000 for the GM device. Most of this wide variation is attributable to performance differences and to the use of assorted technologies (sonic, infrared, capacitance, radar, and laser). Many of these systems are built on a customized basis and costs would, of course, be reduced in a production run. The NASA technology costs are estimates; considerable engineering development would be required before a production figure could be obtained. The selection of hardware would depend greatly on the actual AGT or AMTV guideway.

Trade-offs

The industry has yet to standardize any one type of AGT or AMTV. Therefore, each vehicle and its obstacle detector becomes a custom order. Accuracy in the range and size of the obstacle detected can often be traded against cost.

Production Costs

Fortunately, the cost of the solid-state technologies used in each of the detectors surveyed is decreasing as new production techniques are found. The programming for the necessary logic circuits is readily available and inexpensive. Price breaks would probably appear at runs of 100 units, 500 units, and 1,000 units.

Contact Bumper Costs

Contact bumpers cost \$300 to \$500 per face. All the commercially available vehicles shown in Table 4 have a contact bumper.

[illegible][illegible]

21

[illegible][illegible]

100

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VI MARKET FORECAST

Automated Guideway Transit Systems

AGTs represent a limited market for obstacle detectors, based on the information presented in this section:

Market Size

As Table 1 (page 8) indicates, approximately 20 AGT systems are in operational service in the United States. Other than a contact bumper on the AIRTRANS system in the Dallas/Fort Worth airport, none of these systems have any form of obstacle detector. These AGTs have not incurred collisions because of the well-isolated nature of the guideway. Because the managements of the systems do not perceive any obstacle threats to their properties, no market for a detector currently exists.

Emerging Trends

Despite uncertainties in local support, funding formulas and preliminary engineering proposals, Miami, Detroit, St. Paul, Houston, and Los Angeles are proceeding with varying plans for AGTs in their downtown areas. With the deployment of AGTs into urban areas, the potential for collision with city trash and objects left by vandals increases significantly.

Gasoline shortages will increase the demand for more AGTs, but the long lead time between acceptance of proposals and installation of actual functioning hardware greatly restricts the anticipated number of AGTs that can be completed over the next 20 years. Only an estimated two or three new systems using an average of 10 trains each are expected to be brought into operation per year. Because these will undoubtedly be placed in urban areas, a need for an obstacle detector will be established. Thus, within the next 20 years, a market for a total of 400 to 600 units will develop.

Commercialization Potential

Using an average price of \$5,000 per unit and a 20-year market total of 400 to 600 units, the total gross sales from 1980 through 2000 are estimated to be no more than \$3,000,000 (1980 dollars). Viewed as an annual maximum of \$150,000 gross sales, it is unlikely that a manufacturer would tool up for this type of line. Therefore, no

production runs are anticipated, and AGT obstacle detector production will remain a customized, job-shop type of order.

Automated Mixed Traffic Vehicle System

The JPL AMTV is equipped with an array of long- and short-range proximity sensors that can detect obstacles far enough ahead of the vehicle to permit a controlled stop. It is not adequate for detecting people moving in mixed traffic, however, because the current sensor array is not sufficiently efficient to stop the vehicle from hitting a pedestrian who steps in front of it from an angle. Until the field of scan for the sensors can be improved, safe mixed traffic operations cannot be accomplished.

Market Size

AMTVs may find their first application in shopping centers at selected locations, in the larger retirement communities, and in recreation areas and amusement parks. An initial estimate of the number of such sites in the United States suitable for AMTV systems is as follows: shopping centers, 170; retirement communities, 25; recreation areas, 151; for a total of 346. Some additional application areas may also be on a limited number of university or college campuses.

Emerging Trends

Near-term deployment possibilities are limited because at the present, a suitable vehicle has not been fully developed. Additional technology development is required, particularly in the area of sensors, as well as a public demonstration of the AMTV concept. Actual market penetration will be predicted on the successful results of these efforts.

Commercialization Potential

A 1-mph AMTV seems to solve many of the short-range transportation problems of the elderly and the handicapped. It would provide the quality of transport desired at a reasonable cost. Fabrication and construction costs would be minimized. Unfortunately, those attributes that would make the 1-mph AMTV desirable for elderly and handicapped riders would seriously limit its market potential. Initial markets for such a vehicle, by SRI's estimate, would fall even below the range estimated by GM for its EPM vehicle (50 vehicles in 12 installations per year). Application areas over the next 20 years might include: adult and retirement communities (200 vehicles), medical centers (50 vehicles), and possibly 200 more vehicles spread over activity centers such as shopping centers, airports, railroad terminals, and multiuse developments.

Obstacle detectors for AMTV require more sophisticated hardware. Using an average estimated price of \$6,000 per unit and a 20-year market total of 250 to 450 units, the total gross sales per AMTV use from 1980 through 2000 are estimated to be no more than \$2,700,000 (1980 dollars). This produces an annual average sales of \$135,000.

Regulation

As of the date of this report, no government regulations specifically require obstacle detection on any form of automated vehicle. If such a regulation were enacted, an additional market of 20 to 30 units would arise for the existing systems.

Total Market

Although the combined total number of units estimated for AGT and AMTV use equals 650 to 1,050 units by the year 2000, this represents only 32 to 53 units per year, with annual gross sales of approximately \$285,000. This dollar volume is too low, to justify a production run by a major manufacturer, but it might be sufficient for smaller companies or job-shops.

VII SUMMARY AND CONCLUSIONS

The 20 AGTs in public use currently do not have noncontact obstacle detectors nor do their operators believe they have a use for one. Future expansion of AGTs into urban areas, where debris and other obstacles may create a need for such units, would open a predicted market of 20 to 30 devices per year through the year 2000.

For successful operation of an AMTV, an obstacle detector must be included. Plans for approximately 23 to 32 vehicles per year are forecast. This quantity, in combination with the number required for AGT use, would produce a market that could successfully be supplied by a small manufacturer or job-shop.

Table 5 describes the sonic, capacitance, infrared/optical, guided radar, and probe contact obstacle detectors both currently available and under development and compares the requirements such devices must have for AGT and AMTV use. The conclusions based on this comparison are as follows.

Automated Guideway Transit Systems

- The need for an AGT obstacle detector has not been established because --
 - The 20 AGTs in public operation do not use a noncontact obstacle detector.
 - The operators of these 20 AGTs do not believe they have a need for one.
 - Few of the AGTs running today have had any collisions.
 - As yet, no government regulations require the use of an obstacle detector.
- Currently available obstacle detectors do not meet the requirements set forth in this report for AGT or AMTV use because --
 - None have sufficient range or reliability
 - Seeing through weather continues to be a problem.
 - Other than the Queen's University guided radar obstacle detectors, none have the capability of seeing around corners.
- The projected market is too small for a manufacturer to supply only to the AGT users, that is --
 - The projected market is for only 20 to 30 units per year.

Table 5
DESCRIPTION OF OBSTACLE DETECTION SYSTEMS

Detector type	Unspecified	Currently Available System			Systems Under Development			NASA Technology						
		Scientific Technology Corp. (JPL)	Clark Equipment Co. (JPL)	Star Motor, Inc. (JPL)	Atcon, Inc. (JPL)	Mobility Systems, Inc. (JPL)	Onia Elevator Co. (JPL)	IBM Transportation Systems (JPL)	Queen's University (JPL)	JPL Infrared/optical	JPL Laser	Spacelab Politechnic Institute (JPL)		
Range														
Primary range (ft)	50	12-20	20-25	15	8-10	1-5	10-15 ^a	10	10	5	Section emitting of 1 mile	25	25	90
Secondary range (ft)	10	8	10	6	7	None	6 ^a	0.5	5	None		8	None	15
Smallest object detectable (inches in diameter)	5	N/A	N/A	8	N/A	3	N/A	1	N/A	N/A	10	10	10	N/A
Cost (\$)	1,200 ^b	2,000	800 ^d	2,500	1,500	1,200	6,000	2,000-5,000 ^b	N/A	5,000 ^b	N/A	6,500 ^b	N/A	N/A
Area around corners	Yes	No	No	No	No	No	No	No	No	No	Yes	No	No	No
Sea weather (i.e., snow, rain, fog)	No	Yes	Partially	Yes	Yes	Yes	Yes	Yes	Yes	Partially	No	Partially	Yes	Yes
Capable of warning on collision course (only one only) ^c	Yes	No	Yes	No	No	No	No	No	No	Yes	No	Yes	Yes	Yes
Vehicle description	None	Tractor trailer	Tractor trailer only (supplier to IBM firm)	Tractor trailer (Bentley)	Tractor trailer (Bentley)	Self-propelled platform (Bentley)	Tractor trailer (Bentley)	Self-propelled platform (Electrolytic)	Tractor trailer (Bentley)	Self-propelled platform (Bentley)	Tractor trailer (Bentley)	Self-propelled platform (Bentley)	Tractor trailer (Bentley)	Tractor trailer (Bentley)

^a Function designed for specific equipment.

^b JPL estimate.

^c JPL estimate.

^d JPL estimate.

^e Refers to technology, design, and programming changes required.

N/A, not applicable.

Not available.

Should not exceed 1% of vehicle cost.

Foot transmittance and three receivers.

- Annual sales of a maximum of \$150,000 are predicted.
- Therefore, no further development of a noncontact obstacle detector for AGTs should be undertaken until a need is more firmly established.

Automated Mixed Traffic Vehicle System

- The need for an obstacle detector for AMTV operation is crucial because --
 - A large number of obstacles can be expected due to mixed traffic operation.
 - Even though partially protected guideways can decrease the technical requirements for an obstacle detector, obstacles will still be encountered at boarding points.
- Currently available obstacle detectors do not meet the requirements for AMTV use for the same reasons that those for AGTs do not meet requirements.
- The projected market is not large enough for a manufacturer to supply only to AMTV users but if AGT users were included, small manufacturers might be interested in producing the units as an add-on product line or in a job-shop situation. The market data are as follows:
 - The projected market for AMTV use is 12 to 24 units per year.
 - Annual AMTV sales of a maximum of \$135,000 are predicted.
 - Anticipated combined AGT/AMTV obstacle detector sales are approximately \$285,000.
 - Product liability problems in the event of an accident may outweigh commercial gain.
- More development work is needed on the NASA technologies before AMTV requirements can be met. Areas requiring development are:
 - Ability to recognize objects on a collision course from side areas.
 - Ability to see around corners.
- The ability to see around corners is sufficiently important that AMTVs should make use of sensors and related equipment in the wayside.
 - Modified versions of the Queen's University guided radar system that is under development may provide the solution.
 - Wayside sensing subsystems must be low in cost, reliable, and provide an adequate margin of safety.
 - Additional uses for wayside detectors, such as intrusion detection and automotive traffic control, would greatly increase the market for these devices.

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